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1. Your reference — 2566

2. Patent application number *(The Patent Office will fill in this part)* — 0217047.0

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

University of Southampton
Highfield
Southampton
So17 1BJ

Patents ADP number *(if you know it)* — 798470001

If the applicant is a corporate body, give the country/state of its incorporation

4. Title of the invention

Optically Induced Refractive Index Modification in Optical Materials.

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

~~Centre for Enterprise and Innovation~~
~~University of Southampton~~
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~~Southampton~~
~~So17 1BJ~~

D Young & Co,
21 New Fetter Lane,
London,
EC4A 1DA.

Patents ADP number *(if you know it)* — ~~8019325001~~

PFS1/77
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6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
a) any applicant named in part 3 is not an inventor, or
b) there is an inventor who is not named as an applicant, or
c) any named applicant is a corporate body.
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No.

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Continuation sheets of this form	
Description	11
Claim(s)	2
Abstract	1
Drawing(s)	4 — Total 18 pages.

10. If you are also filing any of the following, state how many against each item.

Priority documents	
Translations of priority documents	
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature Ployaert Date 23/7/2002

12. Name and daytime telephone number of person to contact in the United Kingdom: Mylène Ployaert 023 8059 4680.

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TITLE OF THE INVENTION

OPTICALLY INDUCED REFRACTIVE INDEX MODIFICATION IN OPTICAL MATERIALS

BACKGROUND TO THE INVENTION

The present invention relates to the production of refractive index structures in optical materials through the use of a scanned, projected or otherwise incident light source interacting with the surface region of the host material.

The character of the optical structure in relation to aspects such as its depth, width, numerical aperture, permanency, and other such optical properties is controllable through the duration, focussing, power density, scan speed and wavelength of the incident light source. In all cases, the implementation of the technique is simple, direct, and a one-step process, in contrast to other existing techniques that are inherently multi-step in nature, and usually require sequential steps involving photolithographic processing, and clean-room preparation conditions.

In a particular class of optical materials, ferroelectric single crystals such as lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$) have an increasingly widespread usage in the photonics industry due to their diverse range of nonlinear, piezoelectric, pyroelectric, electrooptic, photoelastic and photorefractive properties. Large quantities of high optical quality congruent (lithium deficient) lithium niobate single crystals are grown by many crystal companies for a variety of applications including integrated Mach-Zehnder optical modulators for telecommunications [1], surface acoustic wave (SAW) devices [2] and domain engineered periodically poled materials for efficient quasi-phase-matched nonlinear optical devices for harmonic and parametric wavelength conversion applications [3].

Many of these applications for which the efficiency or speed depends on the product of interaction length and optical intensity require the fabrication of (low loss) optical channel waveguides. Waveguide fabrication in these materials has been much researched in the past few decades, but the techniques that are currently most favoured within industry still rely on multi-step, complicated and time-consuming processes, that require clean-rooms, high temperatures, and the use of undesirable and potentially harmful chemicals. For $LiNbO_3$ waveguide fabrication, the most widely

used methods are: (a) Ti: indiffusion, (b) proton exchange. Whereas these methods are capable of producing low loss waveguides, they are all inherently multi-step and invariably require the sequential processes of photolithographic patterning or masking, involving many photoresist processing steps, diffusion at high temperature or immersion in ion or chemical exchange baths, surface cleaning, and final processing. All of these must be performed under clean-room conditions, and have a non-negligible implication for safety requirements and environmental issues. Additionally, in the case of proton exchange for example only TM (transverse magnetic) modes can propagate within these guides, and there is an additional process step required for the restoration of the nonlinearity due to ion exchange induced damage of the material.

Replacing these existing techniques with a radically simpler, more flexible, faster and cheaper **single-step** process is therefore highly desirable, and this is the invention described within this patent.

The advantages of such a direct writing process can be conveniently summarised in the following table.

	Proton exchange	**Ti: indiffusion**	**Direct- writing**
speed	Slow: hrs/days	Slow: hrs/days	Fast: minutes
loss	Low	low	Low
steps	multi	multi	Single
flexibility	limited	limited	High
Clean-room required?	Yes	Yes	No

SUMMARY OF THE INVENTION

The present invention is based on the experimental evidence that there is an interaction between incident light and the surface of lithium niobate ($LiNbO_3$) single crystals, such that waveguiding tracks can be written by simple illumination of the surface. The laser beam can be scanned across the material, or alternatively, the material can be scanned beneath the stationary laser beam, or a combination of both.

For the correct fluence of incident light the surface of the material is not damaged to any appreciable or noticeable degree, but the absorbed light affects the material properties, thereby leaving a permanent change to the irradiated material. The refractive index is increased in this region, leading to the formation of a track whose width is a function of the width of the incident laser beam. Once the incident light is removed, this permanent change has resulted in an optical waveguide structure, thereby providing a means for direct writing to a specific position on the surface of the ferroelectric material.

Accordingly, a first aspect of the present invention is directed to a method of inducing a localised change in refractive index in a sample of ferroelectric material, comprising:

applying a light source of sufficiently high intensity to the surface of the material, to define the desired position for induced refractive index change;

scanning the relative positions of the incident light source and the material to be irradiated. This can involve a stationary material and scanned light source, or stationary light source and scanned material, or a combination of the two;

removing the presence of the light source, to leave the material with a modified refractive index pattern on or near the surface of the material.

This method had immediately attractive features, as it is extremely simple, does not require the use of clean-room facilities, depositions of photoresist or other such materials, does not require the use of potentially toxic or hazardous chemicals, is highly controllable and adjustable and can be used to write structures of specific size, shape, depth, width and length.

In a preferred embodiment, the method further comprises optimizing the choice of light fluence, scanning speed and spot size for the illumination source.

In a preferred embodiment, the light source is a laser source of a wavelength that will be efficiently absorbed at or near the material surface.

In a preferred embodiment, the light source is a UV (ultraviolet) laser light source, at or near a wavelength below the value of 350nm

In a preferred embodiment, the UV laser light source is a continuous wave source, that possesses an optimum beam quality, thereby enabling tight focussing of the irradiating light.

Advantageously the ferroelectric material is one of lithium niobate, lithium tantalite, $KTiOPO_4$, $RTiOAsO_4$, $RTiOPO_4$, $BaTiO_3$, $KNbO_3$, or any other suitable mixed solid solution host such as the $Sr_xBa_{1-x}NbO_3$ family of tungsten bronze crystals.

A second aspect of the present invention is directed towards the fabrication of an optical waveguide layer within the surface region of the crystal. A raster scan of the light source across the sample surface, or a scan of the surface beneath the stationary light source, or alternatively a combination of these two methods will lead to a surface area which as been modified in its refractive index. This layer may be referred to as a planar waveguide layer.

A third aspect of the present invention is directed towards the fabrication of an optical waveguide channel within the surface region of the crystal. A raster scan of the light source across the sample surface, or a scan of the surface beneath the stationary light source, or alternatively a combination of these two methods will lead to a surface area which has been modified in its refractive index. This layer may be referred to as a channel waveguide layer.

A fourth aspect of the present invention is directed towards the fabrication of more complex two dimensional optical circuitry written into or near to the surface region of the ferroelectric material. Pathways within the surface region comprising channels, junctions, overlaps, crossings, splitters, adjacent element with spaces between, and so forth can be written using the above technique.

A fifth aspect of the present technique is directed towards the writing of gratings, or other periodic structures, either by direct write and scanning, or else by

the use of a diffractive or otherwise interferometric patterning techniques, such as the use of a phase mask, or alternative amplitude or phase grating.

A sixth aspect of the present technique is the writing of any such structure, with arbitrarily complex spatial patterning into or near to the surface of the ferroelectric material.

A seventh aspect of the present technique is to imprint a structure into or near the surface of the ferroelectric material by contact printing, or otherwise by projection reproduction, using a technique other than by serial scanning of the light source or material to be irradiated, or combinations of these two techniques.

An eighth aspect of the present technique is to use combinations of the seventh and earlier aspects to pattern a refractive index change using this method, and subsequently use scanning techniques to trim or modify or otherwise alter the structures for designer based optical circuitry requirements.

BRIEF DESCRIPTION OF THE DRAWINGS

To illustrate how the direct writing process can be implemented for surface or near-surface modification to ferroelectric host materials, reference is made by way of example to the accompanying drawings, in which :

Figure 1 shows a schematic representation of the experimental arrangement for scanning a source of UV light, from a laser beam in this embodiment across the surface of the ferroelectric material whose refractive index is to be modified. In this schematic, the laser beam is stationary, while the sample beneath is scanned.

Figure 2 shows a schematic representation of the experimental arrangement for scanning a source of UV light, from a laser beam in this embodiment across the surface of the ferroelectric material whose refractive index is to be modified. In this schematic, the laser beam is scanned, while the sample beneath is stationary.

Figure 3 shows an example of the profile of a guided-wave near-field two-dimensional beam profile written using the procedure illustrated in the schematic of figure 1, for guided-wave light at a wavelength of 633 nm from a He-Ne laser beam. For this demonstration, the laser scanning rate was 600mm/min, while the laser power was 30mW

Figure 4 shows an example of the profile of a guided-wave near-field two-dimensional beam profile written using the procedure illustrated in the schematic of figure 1, for guided-wave light at a wavelength of 633 nm from a He-Ne laser beam. For this demonstration, the laser scanning rate was 600mm/min, while the laser power was 40mW.

DETAILED DESCRIPTION

The technique of direct writing of refractive index changes into ferroelectric materials has been applied to congruent lithium niobate single crystals in the first instance. The results of this process have shown that exposure of undoped lithium niobate single crystals to UV radiation under a range of conditions can locally change the refractive index of the irradiated area. We have additionally seen that the refractive index can be raised under specified conditions of irradiation. For the results we have seen, the crystal sample was scanned under the stationary light source, which in this embodiment was a continuous wave UV laser source, as shown in the schematic of figure 1. For a focussed UV laser beam, at irradiances of order 0.5MW cm^{-2}, an optical guiding structure is created that corresponds to a channel waveguide.

In figure 2 there is shown a variation of the writing process in which it is the light source that is scanned, while the sample is stationary. The light source would be scanned through the use of controllable deflection devices such as mirrors, or other addressable devices such as beam deflectors, acousto-optic modulators, liquid crystal scanners, or other such devices.

In this embodiment, using a frequency doubled continuous wave Ar^+ (Argon ion) laser operating at 244 nm and an x-y-z computer controlled high precision translation stage we have written controllable channel waveguides of adjustable depth, width and refractive index values.

Under a range of irradiation conditions, these refractive index channels act as optical waveguides, also of variable width, depth, numerical aperture and induced values of modified refractive index.

RESULTS

Shown in figure 3 is an example of the guided wave structure written in this example by the method illustrated in figure 1. The mode profile illustrated is of a guided wave beam from a He-Ne laser at a wavelength of 633nm, written under a

regime of comparatively low irradiation fluence. It is seen that the profile is relatively extended, indicating that the induced index change is moderate.

Shown in figure 4 is an example of the guided wave structure written in this example by the method illustrated in figure 1. The mode profile illustrated is of a guided wave beam from a He-Ne laser at a wavelength of 633nm, written under a regime of comparatively high (and higher than that of figure 3) irradiation fluence. It is seen that the profile is much less extended (than that of figure 3), indicating that the induced index change is higher (than that of figure 3).

The channels written by the technique are optical waveguiding structures that are capable of guiding both TE (transverse electric) and TM (transverse magnetic) modes. Numerical apertures (N.A.) for single mode waveguides at 633 nm of order N.A.=0.05 have been measured, which would correspond to an induced refractive index change of order $\Delta n \sim 10^{-3}$.

The figures quoted above for N.A., Δn, scan speed, laser fluence and any other such relevant parameters are all under experimental control, and fall within the description covered by this invention.

Guides have been written in the surface of $LiNbO_3$ samples under the following (non-exhaustive) experimental conditions:

the laser power on the sample surface was between 10- 55 mW

the laser beam was focussed down to a spot size of order 1.7μm (radius)

the translation speed of the sample holder was varied between 3000mm/min and 10mm/min.

z face crystals have been irradiated and guides have been produced

y face crystals have been irradiated and guides have been produced.

It is fully expected that x face crystals will also produce effective guided wave structures.

In all the above cases, positive values of refractive index change have been observed.

APPLICATIONS

The invention simplifies significantly the procedure for channel waveguide fabrication in lithium niobate for a wide range of integrated optical applications. The main features of the invention that position this technique as being superior to existing waveguide fabrication methods are:

no requirement for photolithography, metal deposition, high temperature diffusion processes or other multi-step procedures

no need for high grade cleanroom environment

precise mode control and refractive index trimming.

waveguide fabrication even on fragile structures such as lithium niobate cantilevers and membranes,

the process is fast and takes about the 1/100 the time for waveguide fabrication compared with conventional techniques.

In consideration of the above direct benefits, the following non-exhaustive list of applications is given:

1. Fabrication of planar waveguide layers

2. Fabrication of channel waveguide structures

3. Refractive index trimming in existing structures fabricated by other means.

4. Low loss optical waveguides.

5. Fabrication of structures that require guides of arbitrary curvature

6. Fabrication of guides that have junctions

7. Fabrication of waveguide beam splitters

8. Fabrication of optical couplers

9. Fabrication of multiple guides in adjacent proximity

10. Fabrication of tapered or variable width guides

11. Fabrication of buried guides

12. Fabrication of single mode guides

13. Fabrication of multimode guides.

FURTHER EMBODIMENTS

The direct write technique described thus far has immediate application to the fabrication of a wide range of waveguide devices, through the controlled manipulation of the local refractive index.

Further to this technique which has been demonstrated using a wavelength of 244nm, other wavelengths in the near UV, and/or within the bandgap of $LiNbO_3$ and/or near the band edge of $LiNbO_3$ may also prove successful

Also, the invention is not limited to the use of Lithium Niobate. Other ferroelectric hosts such as lithium tantalate, $KTiOPO_4$, $RTiOAsO_4$, $RTiOPO_4$, $BaTiO_3$, $KNbO_3$, or any other suitable mixed solid solution host such as the $Sr_xBa_{1-x}NbO_3$ family of tungsten bronze crystals can be engineered in this fashion.

The ferroelectric host may be doped to include elements such as Zn, Mg in the form of ZnO, or MgO, which are introduced to reduce or ideally remove photorefractive damage.

The ferroelectric host may be doped with atoms or ions to assist lasing or for use as amplifiers, such elements to include rare earths, lanthanides and transition metals.

The ferroelectric material can be in a single domain or multi-domain state prior to exposure to the irradiating light source.

The ferroelectric material can be in the form of periodically poled material, for which the writing of a waveguide would permit subsequent highly efficient non-linear interactions via the process of quasi-phase-matching.

CONCLUSION

Finally, in conclusion, a new method for direct writing of modified index structures in ferroelectric hosts has been described. The advantages over conventional multi-step processes in terms of speed, cost, equipment required, versatility and controllability are described, and considered to represent a distinct advantage over other state of the art techniques.

REFERENCES

1. E. L Wooten *et al* IEEE J. Select. Top. in Quant. Electr. 6, 69 (2000)
2. R. V. Scmidt, I.P. Kaminow, IEEE J. Quant. Electr. 57 (1975)
3. P. E. Britton, H. L. Offerhaus, D. J. Richardson, P. G. R. Smith, G. W. Ross, D. C. Hanna, Opt. Lett. 24, 975 (1999).

CLAIMS

1. A method for modifying the refractive index of optical materials through the interaction of light with the material structure, comprising.

illumination of the material with light at a sufficiently high power density

scanning of the material or illuminating light source to form a two-dimensional pattern or structure

removing the light source to leave a permanently affected area on the sample surface.

2. A method according to claim 1, in which the material under illumination is a ferroelectric host

3. A method according to claim 1, in which the illuminating light source can be a laser beam.

4. A method according to previous claims in which the laser beam has a wavelength in the visible, near UV or UV spectral regions

5. A method according to previous claims, in which the laser has a wavelength in the UV that is near to the bandgap of the material

6. A method according to previous claims, in which the laser has a wavelength in the UV that is beyond the bandgap of the material.

7. A method according to any of the previous claims, in which the power density of the light source is sufficient to induce the required refractive index modification.

8. A method according to any of the previous claims in which the light source is scanned over the sample surface

9. A method according to any of the previous claims in which the light source is stationary and the sample is scanned

10. A method according to any of the previous claims in which the light source and the sample surface are moved relative to one another.

11. A method according to any of the previous claims in which the sample is doped with elements to reduce the photorefractive damage in ferroelectric materials.

12 A method according to any of the previous claims in which the sample is doped with atoms or ions to promote active device structures.

13. A method according to any of the previous claims in which the sample is doped with atoms or ions to promote lasing or amplifying within the host material

14. A method according to any of the previous claims in which the sample is in the form of a single domain structure.

15. A method according to any of the previous claims in which the sample is in the form of a multi-domain structure.

16 A method according to any of the previous claims in which the sample is in the form of a periodically poled or otherwise domain engineered structure.

17 A method according to any of the previous claims in which the sample is illuminated by a mask, or pattern in a parallel illumination fashion

ABSTRACT.

A method of inducing refractive index modifications in ferroelectric materials through the application of light in the form of scanned or patterned irradiation, removing the light to leave a permanent refractive index modified structure. This method can be used to design and engineer surface or near-surface structures in the form of waveguides, junctions, splitters and couplers, for application in optical circuitry, integrated optics, and active waveguide devices.

Figure 1

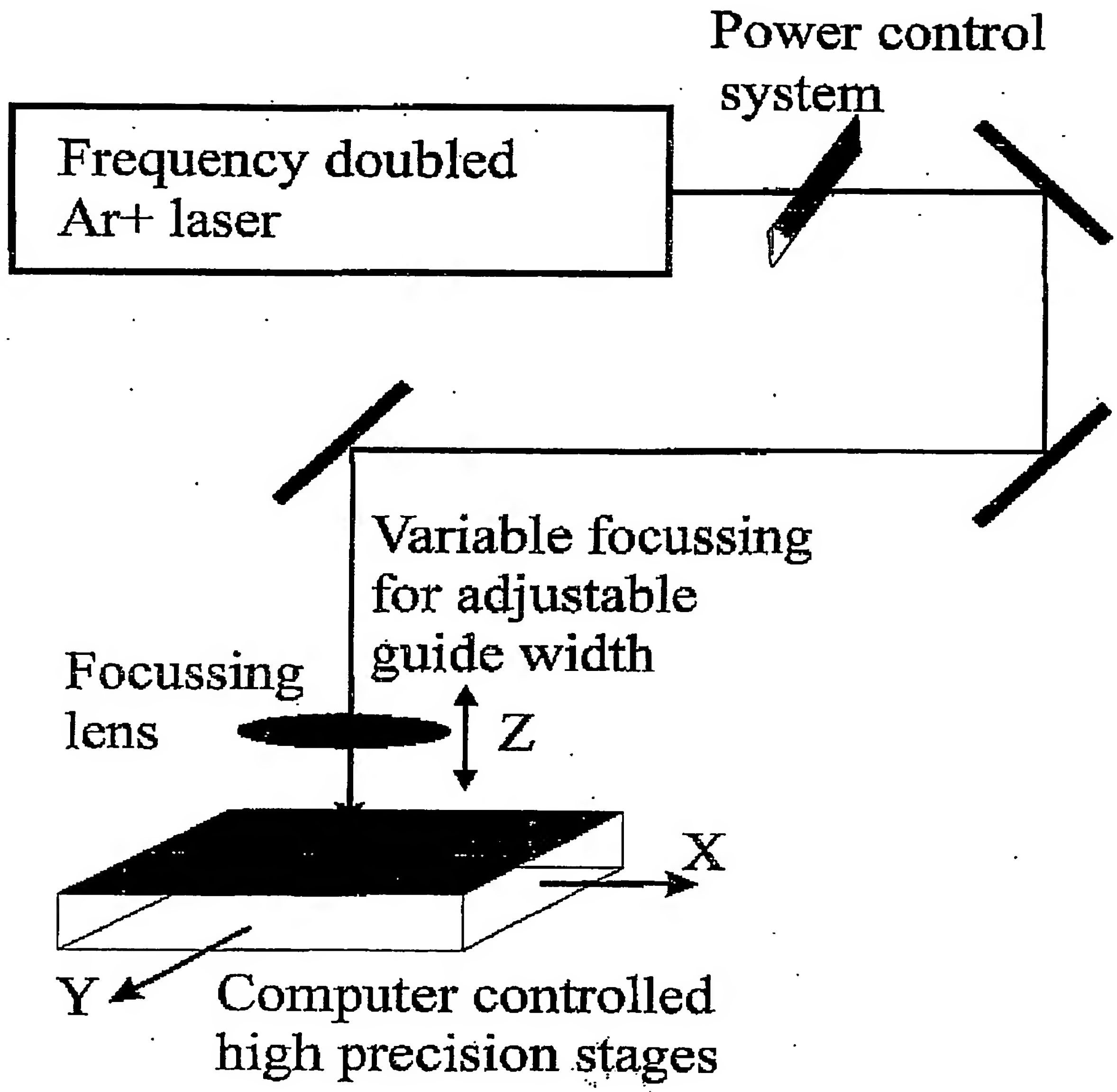
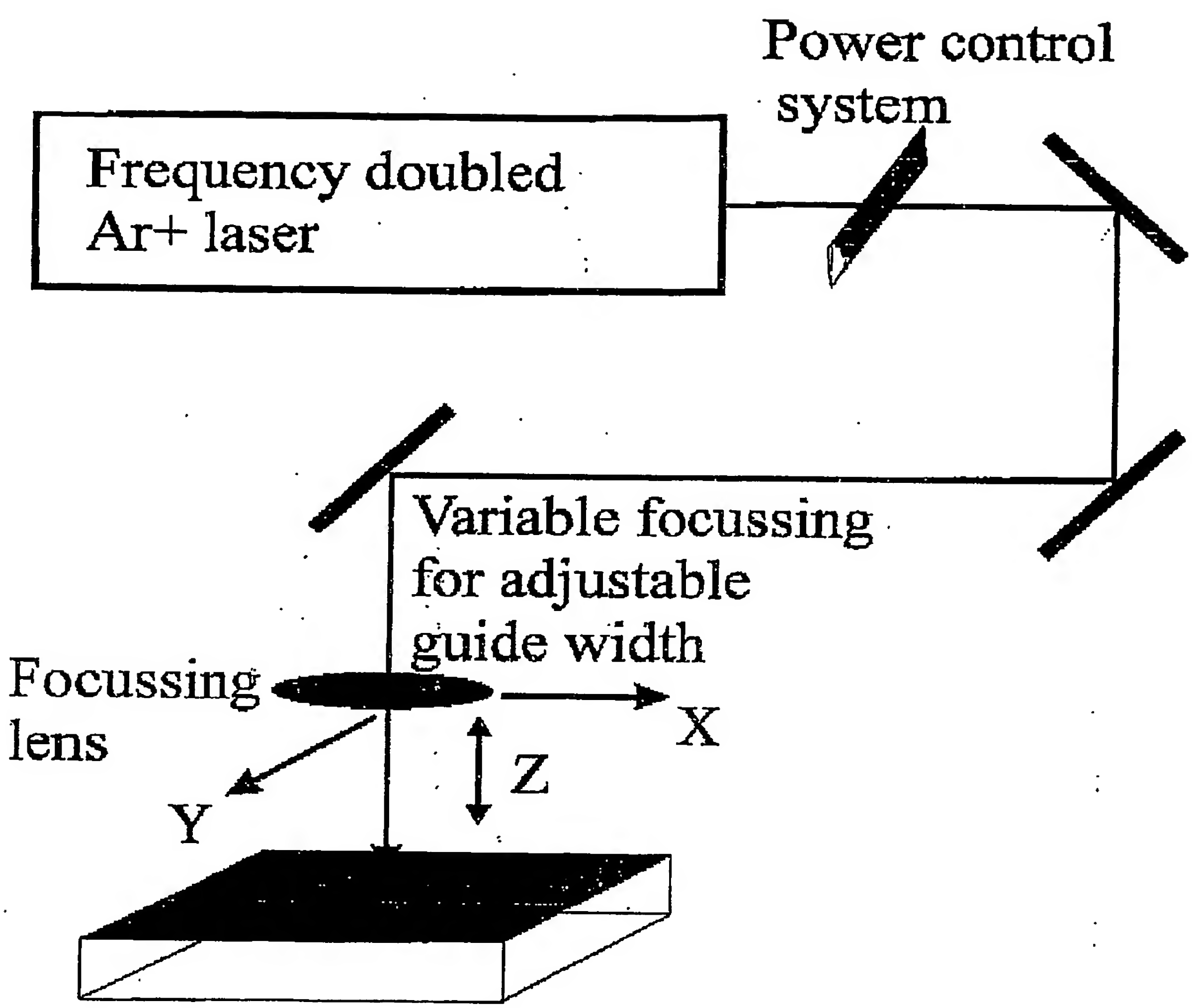

Power control system
Frequency doubled Ar+ laser
Variable focussing for adjustable guide width
Focussing lens
Z
X
Y
Computer controlled high precision stages

Figure 2



Power control system
Frequency doubled Ar+ laser
Variable focussing for adjustable guide width
Focussing lens
X
Y
Z

Figure 3

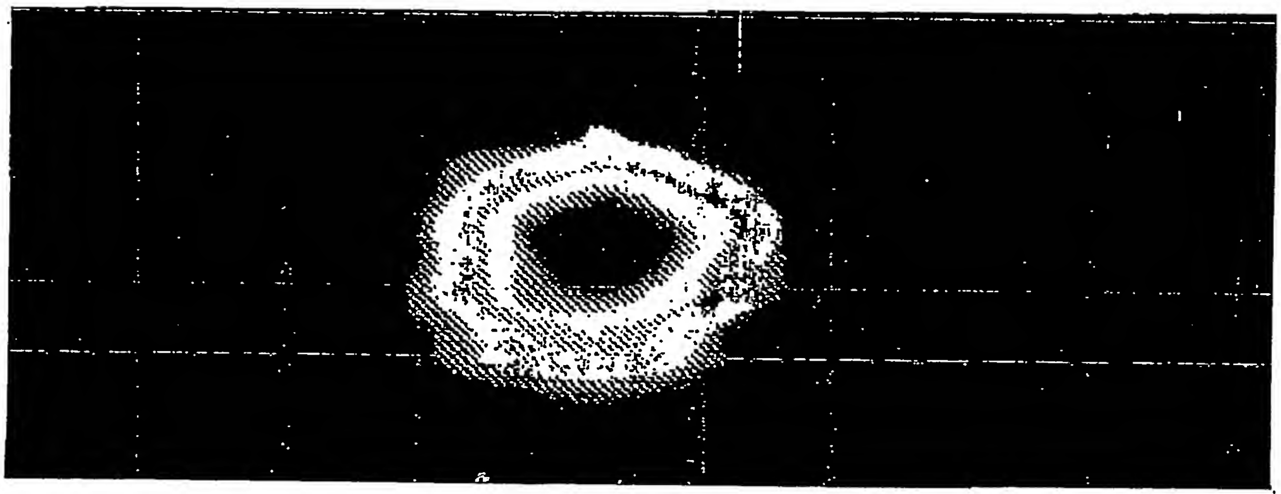


Figure 4